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Approved For Release 2009/08/17 : CIA-RDP88-00904R000100100

Third United Nations
International Conference
on the Peaceful Uses
of Atomic Energy

A/CONF.28/P/308
USSR
May 1964
Original: RUSSIAN

Confidential until official release during Conference

START-UP AND PILOT OPERATION OF THE FIRST UNIT OF THE BELOYARSK NUCLEAR POWER STATION AFTER I.V.KURCHATOV

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1. Design characteristics of the first reactor of the Beloyarsk nuclear power station (БАЭС)

The principal design of the nuclear power station and the reactor design are described in the report to the 2nd International Conference on the Peaceful Uses of Nuclear Energy /1/.

Here only main plant design characteristics and schemes of interest in connection with the nuclear power station start-up are discussed.

As it is known the first reactor of the Beloyarsk power station is thermal uranium-graphite pressure-tube reactor with fuel channels of two types: evaporating channels (ИК) and steam superheating ones (ППК).

In the evaporating channels of the first curcuit 150 atm. water is heated and partially evaporated.

Superheating channels are designed to superheat steam produced in steam generators. 95 atm superheated steam generated in the reactor is fed directly to the turbine. The flowsheet of the plant is shown in Fig.1.

The main characteristics of the primary and secondary coolants are listed in Table I.

Table I.

The main characteristics of the reactor coolant of the Beloyarsk nuclear power station

Nos.	Characteristics	Unit	1st circuit	2nd circuit
1.	Reactor thermal output	Mw	286	
2	Electrical output	Mw	100	
3	Ratio of superheating to evaporating channel output	%	30.0	
4	Coolant flow rate	t/hr	1200	405
5	Coolant pressure:			
	at reactor inlet	atm	155	110
	at reactor outlet	atm	150	95
	before the turbine	atm	150	90
6	Coolant temperature:			
	at reactor inlet	^oC	300	316
	at reactor outlet	^oC	340	510
	before the turbine	^oC	340	500
7	Steam content at evaporating channel outlet	%	33.6	500

It is characteristic of the reactor structure that there is no pressure vessel and pressure-tube fuel elements are used as evaporating and superheating fuel channels.

Heat is removed only from the inner surface of the tubular fuel elements (by boiling water in evaporating channels and steam in superheating ones). Coolant distribution over separate channels makes it possible to remove easily steam-water mixture from the reactor by means of small diameter tubes and to locate the steam separator outside the reactor. In addition, fuel element design makes it possible to control fuel element cooling, the integrity and power of every channel and the use of pressure tube fuel elements prevents fission products leakage into the coolant circuits and the turbine in case of a fuel element failure. Fuel channels are positioned in the 200x200 mm reactor graphite moderator blocks and are connected to the coolant circuit conduits at the reactor upper plate. This will make fuel channel refueling more convenient, in particular, spent fuel channels will be patially replaced to increase noticeably the degree of the fuel burn-up.

1.66 g/cm^3 dense graphite is the main neutron moderator of the reactor.

As there is little or no water in fuel channels this affects slightly the effective neutron multiplication factor because of compensation of water influence on thermal utilization factor and U^{238} resonance absorption escape probability. Therefore in the reactors of the type described transition from water cooling conditions to cooling by steam-water mixture or steam brings about small reactivity change. From this point of view considerable steam content is permissible in evaporating channels, this results in coolant flow rate reduction and decrease in power required to pump it. Critical heat fluxes limit steam content in reactors of the type.

The flow sheet of the nuclear power station makes it possible to operate without primary coolant boiling at 50% power level of the nominal.

Reactor fuel channel design consisting of six fuel elements has been described /1/. Tubes of evaporating and superheating channels are made of stainless steel. U-Mo alloy is used as fuel Fuel and structural materials have been chosen as a result of a extensive programme of material and technological experiments including in-pile fuel element tests to determine fuel burn-up level under operating conditions /2/.

Pipes and auxiliary process equipment are made of following materials:

Primary circuit: a) Pipes, stainless steel,

b) Separator, low-alloy carbon steel clad with stainless steel.

c) Circulating pumps, stainless steel

Secondary circuit: a) Steam pipes from the evaporators to group collectors, stainless steel.

b) Steam pipes from the superheated steam collector to the turbine low-alloy carbon steel.

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d) The primary circuit components of evaporators and preheaters of the steam generator, of stainless steel, the secondary ones low-alloy carbon steel.

While designing the power station experiments were carried out in the plant start-up procedure, in particular in the reactor coming up to boiling conditions in the primary circuit and in transition from the superheating channels cooling by water and steam-water mixture to cooling by steam. The reactor heating and coming up to operation at nominal power level was studied without any external heat source use. Operation under conditions mentioned was performed by means of usual plant equipment. A bubbler and a start-up condenser were included in the plant flowsheet on the basis of start-up conditions studies. The bubbler is provided for steam-water mixture dumping before the turbine starts operating under scram or other conditions of sharp decrease in the turbine load. The start-up condenser is used to remove heat in case the turbine condenser is not operating.

The purposes of all other units of the plant shown in Fig.1 are well known.

Calculations and experiments in start-up regime to determine the range of flow rates without pulsations as a function of steam content at different pressures and orificing conditions to prevent pulsations have shown that no difficulties arise in transition to boiling in the primary circuit, in particular there are no flow rate pulsations in separate channels if the pressure in the circuit is not more than 80 atm. In this case the transition to boiling operation was performed by excess water dumping to water treatment system tank. To maintain water level in the separator, to prevent boiling at the suction branch pipe of the circulating pump and to eliminate pressure fluctuations in the primary circuit it is necessary to ensure normal heat removal by the secondary coolant in the steam generator.

Transition from superheating channels water cooling to steam cooling has been checked out in a loop of the First Atomic Power Station of the USSR and at a special stand simulating the plant flowsheet. Two starting regimes have been studied:

1. Gradual water substitution by steam-water mixture first

ICE

and then by steam.

2. At 2-3% power level the removal of water from superheating channels by steam generated in evaporators at reduced pressure by increasing the amount of secondary coolant dumping to the bubbler.

The second regime was approved to be used. Thus the start-up procedure of the reactor-turbine unit is the following:

1. Filling the circuits with water and then heating them up to 180°C at 5-10% power level and establishing the level in the bubbler.

2. The plant heating up to 230°C at 10-15% power level.

3. Establishing the level in the evaporators and blowing through the superheating channels at 2-3% power level.

4. Rising reactor power level to 20% and increasing secondary circuit pressure up to the nominal.

5. Establishing the level in separators i.e. bringing primary coolant to boiling.

6. Feeding steam to the turbine and further power rising.

II. Power station start-up

To check up preliminary results of theoretical and experimental investigations in transients and start-up conditions a step programme was developed to carry out experiments in physi and the plant operation at power. This has ensured a through check up of reliable operation of separate components and units and of the plant as a whole. The nuclear power station start-up sequence is the following:

1. Studies in the reactor physics.

2. The circuit scavenge, tests and pilot operation of plant equipment.

3. Reactor operation without superheating channels.

4. Reactor operation with some superheating channels installed.

1. Reactor physics studies

The first reactor of the Beloyarsk power station start-up

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took place in 1963 and the reactor went critical in September, 1963.

While designing the reactor the main physical characteristics were measured at a subcritical assembly.

While charging the Beloyarsk reactor with fuel channels measurements were made to determine physical characteristics more precisely, to study different control rods worth, space distribution of power density, reactor frequency response and dynamic reactivity effects. The full charge of the reactor consists of 500 evaporating channels with 2% enriched uranium (ИК-2), 230 evaporating channels with 1.5% enriched uranium (ИК-1.5) and 268 superheating channels with 1.5% enriched uranium (ППК-1.5). In addition, there are 64 compensating rods of boron steel and 16 scram rods of B_4C.

Different critical loadings were investigated during this stage of experiments. Special start-up devices made to order were as follows:

a) three log pulse channels,

b) six linear pulse channels,

c) two log current channels,

d) three linear current channels,

e) two reactor-period meters,

f) two reactivity meters.

Experimental instrumentation comprises $\beta - \gamma$ and $\gamma - \gamma$ coincidence circuits, standard counters and a special demand and analyzer of the reactor power harmonical fluctuations (ЗАГ).

Critical systems consisting of ИК-2 channels with water and without it, mixed systems consisting of ИК-2 and ИК-1.5 channels with water and without it with ratio of 2 to 1 as well as design full reactor charge were investigated. Experimental critical loadings are listed in Table II.

Table II.

Critical loadings of the Beloyarsk Nuclear Power Station reactor

Loading composition	No. of channels	
	with water	mithout water
ИК-2	107	128
ИК-2 и ИК-I.5 with ratio of 2 to 1	177	222

The following parameters have been measured by means of specially made fuel channels:

a) resonance escape probability in the lattices

with water $\varphi = 0.858 \pm 0.10$

without water $\varphi = 0.838 \pm 0.010$

b) fast fission factor $\mu = 1.027 \pm 0.005$

c) neutron distribution and cadmium ratio over the reactor radius and height have been determined by activation technique, miniature fission chambers and control rod oscillation technique.

The reactivity effect due to water removal from ИК channels, ППК channels and control channels was measured for the reactor full charge. The reactor graphite stack filling with water was studied too. It has been shown experimentally that reactivity effect due to water removal from the fuel channels is not great: water being removed from 268 superheating channels, $\Delta K/K = +0.07\%$ and for 730 evaporating channels $\Delta K/K = -0.6\%$.

As determined by experiments, the ratio of ИК-2 channel power density to ИК-1.5 channel power density is 1.27 which happened to be very close to the predicted value of 1.26. While determing the neutron fields near the compensating rods it has been stated that rod insertion into the core results in neutron flux decrease by 26% in the neghbour fuel channel and by 14% in the fuel channel positioned at 300 mm from the rod.

Total control rod worth in a cold reactor is:

64 compensating rods, 7.5%;

2 control rods, 0.18%;

16 scram rods, 2%.

Design excess reactivity is about 2% higher than the measured one. The analysis of errors in separate values used in calculations shows that the mean-root-square error in design value of K_{eff} is 2 - 2.5%.

The design core life is achieved by changing the ratio of 2% enriched uranium channels to 1.5% enriched uranium channels. Alongside with the measurements mentioned above the power coefficient of reactivity at coolant operating characteristics proved to be $\frac{\Delta K/K}{\Delta N/N} = 1.5 \cdot 10^{-2}$

During the reactor start-up ion chambers were calibrated, a reactivity meter and devices for determinations of power distribution (without disturbing reactor operating conditions) by compensating rod oscillations were tested and found ready for operation.

2. Circuit scavenging, tests and pilot operation of power equipment.

The reactor and the plant equipment having been mounted, the primary and secondary circuits as well as the cooling circuits of control rods and other auxiliary systems have been scavenged before the start-up of the reactor. The scavenging of the main circuits have been done without using the reactor fuel channels by means of by-pass pipes temporarily installed.

The primary circuit has been twice scavenged by filling and dumping demineralized water at a temperature of 80-90°C. Then the circuit has been scavenged by circulating demineralized water three times. The scavenging resulted in the following water composition:

clorine-ion, 0.025 μg-equiv/litre
hardness, 5 μ g-equiv/litre
alkalinity, 3 μ g-equiv/litre
SiO_3, 0.06 mg/litre
Fe, 0.05 mg/litre

The secondary circuit has been scavenged by monoamonium nitrate and then neutralized by ammonia. Deaerators, feed water preheaters Nos. 6, 7, 8, 9, the first and the second stage preheaters, evaporators, high pressure pipes have been scavenged in the same way. Solution has been circulated in the circuit by a condensate pump connected to the main circuit with temporary pipes. Before the chemical scavenging the circuits have been scavenged with demineralized water at a temperature of 80-90°C circulated by a feed pump. to remove suspended particles of sand, barb, etc. The suspended particles have been trapped by filters positioned near suction nozzles of feed pumps.

After the chemical scavenging, the circuit has been filled with deaerated demineralized water and the condensate pump has been started.

The initial solution concentration in the circuit was 2.4% and then it was reduced. Monoamonium nitrate has been circulated during 10 hours at a temperature of 95°C. The solution has been substituted by deaerated water in the circuit at a flow rate of 15-17 t/hr. The solution has been replaced till the scavenging water concentration was 2000 mg/litre and pH was 7. Then the circuit was filled with 500 litre of 25% ammonia to neutralize the circuit. The ammonia solution has been circulated till the scavenging water contained 8-2[illegible] mg/kg of Fe and pH was 7.3. Then the ammonia solution has been partially replaced by deaerated water, fluoresceine being added to determine the integrity of the evaporator pipe systems. Testing and pilot operation of process equipment, fittings and control and process instrumentation have been carried out while the circuit scavenging. In particular, the coolant flow rate through fuel channels has been controlled according to the power curves obtained during the investigations of the reactor physical characteristics. The system of filling the reactor stack with nitrogen, the fuel element integrity control system and the control system of leak tightness of pipes, etc. have been tested.

3. The reactor operation without superheating channels

The processes of water level establishment in evaporators and separators as well as the transition from water cooling superheating channels to steam cooling have been studied and tested at this stage of the experimental programme. The transition from water cooling to steam cooling has been carried out in the following way: two ППК without fuel elements have been installed, the pipes of the rest of superheating channels that the coolant enters and leaves through have been shut with crosspieces, their hydraulic resistance being equivalent to that of superheating channels.

Simultaneously the secondary circuit has been finally scavenged by water at elevated temperatures and the circulating water quality has been brought to the conditions required.

When scavenging the circuits, the products of the scavenging gathered in the filters installed before the primary circuit circulating pump and in the pipes at the outlet of the evaporators.

In addition, the following parameters have been checked up at this stage of the programme:

a) hydraulic characteristics of the circuits. Actual characteristics of the primary circuit at operating temperatures and characteristics of the secondary circuit while operating with saturated steam have been determined,

b) hydraulic stability of coolant flow rate through separate channels,

c) throughput of valves before the bubbler,

d) operation of pressure regulators, water level and feed water flow rate controllers, etc,

e) establishment of the level in the bubbler,

f) efficiency of process and control instrumentation.

The results obtained at this stage of the experimental programme have confirmed the preliminary results of the investigations of the start-up conditions and it has been stated that a) while ППК blowing through the rate of pressure drop in the secondary circuit is 1.5 atm/min. This is less than the design one (2 atm/min). The disagreement may be explained by some assumptions made while calculating heat transfer from the primary coolant to the secondary one in the evaporators.

b) while establishing the level in the separator the rate of pressure drop in the primary circuit is 1-2 atm/min, it is also less than the design one (4 atm/min). The rate of pressure drop was achieved due to the gradual starting of the evaporators.

It should be noted that the prediction of possible flow rate pulsations in evaporating channels at a pressure less than 70 atm. has been confirmed.

As a result of several runs of superheating channels blowing through it has been stated that the process lasts about six minutes and is more smooth than it was thought before.

4. The plant operation with an incomplete set of superheating channels

At the final stage of the experimental programme the nuclear power plant operation with an incomplete set of superheating channels and with steam of somewhat lower temperature has been investigated. Decrease in steam temperature has been achieved by inserting not all the superheating channels into the reactor. When 192 superheating channels are loaded into the reactor the steam temperature is 390°C. This number of channels having been loaded, the experiments have been made to choose the most acceptable speed of reactor power decrease to 3% power level before blowing through and reactor power rise after blowing through during the reactor start-up and after emergency shut-down.

The chosen and recommended conditions of changing the main characteristics during the transition from water cooling of superheating channels to steam cooling are shown in Fig.2. As it is seen from the curves shown in Fig.2 the temperature of superheating fuel elements is substantially lower than the operating fuel element temperatures at nominal power output during the blowing through of superheating channels. During the scavenging all the parameters undergo a slow and smooth change.

At this stage of experiments the bubbler and quickly operating reducing-cooling plant operation as well as the operation of the regulators of the steam superheat temperature (ПВД-9) have been tested.

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On April 26, 1964 the steam superheated in the reactor was fed to the turbine and the Beloyarsk nuclear power station began to produce commercial electric power. By the time the report was written all the tests and short-term station operation had shown no special features of the plant equipment operation different from those characteristic of the plant equipment at conventional stations.

During the given stage of the start-up special attention has been paid to ensure the required quality of water circulating in the circuits. In particular, to bind oxygen dissolved in water chemically pure water solution of hydrazine hydrate has been injected into both circuits. This makes it possible to maintain the concentration of dissolved oxygen at a level of 0.015-0.02 mg/kg with pH = 9.0-9.5.

The total content of corrosion products is 0.1-0.2 mg/kg. In the circuits there is excess of free oxygen that promotes to neutralize the water radiolysis products. The clorine-ion concentration is not more than 0.025 mg/kg. The radioactivity of primary water (according to dry residuum) is 2.10^{-6} curies/kg mainly from Na^{24} and Si^{31}. The activity of saturated steam (according to dry residuum) is 2.10^{-9} curies/kg and that ot the turbine condensate is 2.10^{-8} curies/kg.

In the future according to the plant start-up programme the reactor is to operate during some months with gradual steam temperature rise from 390°C to 500-510°C and with reactor power increasing. Steam temperature rise will be due to the increase in number of superheating channels being loaded into the reactor till they are 268.

In this period temperature conditions of operation of superheating fuel elements, graphite stack and metal structural members will be investigated. The entrainment of radioactive salts and corrosion products into the turbine and pipes will be studied too, transients will be finally checked out and design parameters of the nuclear power station will be achieved.

At present the construction works and mounting of the second 200 Mw(e) reactor of the same type with one-circuit flow sheet are under may at the Beloyarsk power station. A more detailed information about the second reactor of the Beloyarsk nuclear power station and the promising ways of developing uranium-graphite pressure-tube reactors is presented in a separate report to the present conference /3/.

References

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3. N.A.Dollezhal, I.Ya.Emelyanov, P.I.Aleshchenkov et al., Development of Power Reactors of the Beloyarsk Nuclear Power Station Reactor Type with Nuclear Superheating of Steam, Soviet Report to the Third International Conference on the Peaceful Uses of Nuclear Energy, Geneva, 1964.

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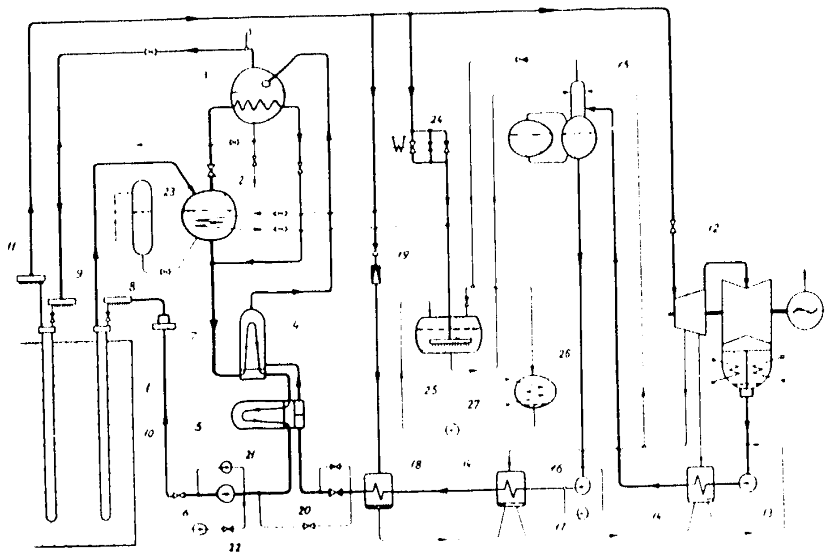

Fig.1. Flowsheet of the first unit of the Beloyarsk Nuclear Power Station:
1 - evaporating channel, 2 - steam-drum, 3 - evaporator, 4,5 - preheaters, 6,16 - circulating and feed pumps, 7 - distributing collector, 8,9 - group collectors, 10 - steam supeheating channel, 11 - superheated steam collector, 12 - turbogenerator, 13 - condensate pump, 14 - regenerative preheaters, 15 - deaerator, 17,21 - emergency feed and circulating pumps, 18 - superheated steam temperature regulator, 19 - quickly operating reducing-cooling plant, 20 - feed valve, 22 - make-up pump, 23 - pressure compensator, 24 - unit of reducing and safety valves, 25 - bubbler, 26 - process condenser, 27 - process condenser pump.

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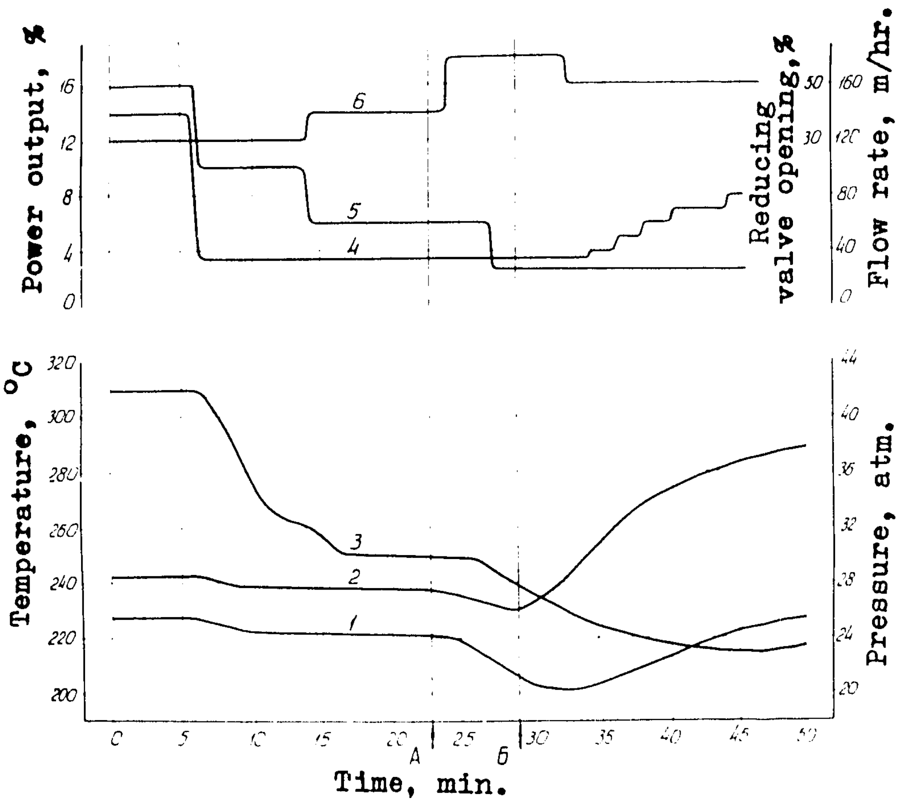

Fig.2. Curves of changes in the main parameters of the plant during transition to steam superheating conditions:
1 - change in coolant temperature at superheating channel outlet, 2 - fuel element temperature change, 3 - pressure change in evaporators, 4 - reactor power, 5 - feed water flow rate, 6 - reducing valve opening at the bubbler inlet; A - beginning of the scavenging of superheating channels, Б - end of the scavenging of superheating channels.

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List of figures to the report "Start-up and Pilot Operation of the First Unit of the Beloyarsk Nuclear Power Station after I.V. Kurchatov"

Fig.1. Flowsheet of the first unit of the Beloyarsk Nuclear Power Station:

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